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EXPRESS LETTER

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San-in shear zone in southwest Japan, revealed by GNSS observations

Takuya Nishimura[1*] and Youichiro Takada[2]

Abstract

A right-lateral shear zone in the San-in region, southwest Japan, has been proposed by previous geological and seismological studies. It locates 350 km north of the Nankai Trough, that is, the main plate boundary between the subducting Philippine Sea and overriding Amurian plates and presumably accommodates a part of the relative plate motion. We present a geodetic evidence of the proposed shear zone using GNSS velocity data. Distinct shear deformation is identified only between ~132.5°E and ~135°E along a coastline which is a part of the proposed shear zone, and we propose to call the geodetically identified shear zone as the San-in shear zone (SSZ). The SSZ is a concentrated deformation zone with a width of ~50 km and can be modeled by a deep creep on a vertical strike slip fault with a creep rate of ~5 mm/year. There are some active faults parallel and oblique to the overall trend of the SSZ, but no single active fault coincides with the SSZ. Lineaments of microseismicity and source faults of large earthquakes are almost oriented in NNW–SSE in the SSZ and oblique to the overall trend of the SSZ. They are interpreted as conjugate Riedel shears. Based on these geodetic, seismological, and geomorphological observations, we suggest that the SSZ is a developing and young shear zone in a geological time scale.

Keywords: San-in shear zone (SSZ), Strain concentration zone, GNSS, Southwest Japan

Introduction

Southwest Japan is situated in the subduction zone where the Philippine Sea plate subducts from the Nankai Trough. Previous studies proposed that some tectonic structures in the southeastern margin of the overriding Amurian plate (i.e., southwest Japan) developed as a result of strain partitioning in response to the oblique subduction of the Philippine Sea plate (e.g., Tsukuda 1992; Gutscher and Lallemand 1999; Itoh et al. 2002) (Fig. 1). One of the most important structures is the Median Tectonic Line, 200 km north of the Nankai Trough. The other is the Northern Chugoku shear zone (NCSZ) (Gutscher and Lallemand 1999) or the Southern Japan Sea Strike Slip Fault Zone (SJSFZ) (Itoh et al. 2002), 350 km north of the Nankai Trough. They are presumably right-lateral strike slip fault zones in the San-in region which is the northern part of westernmost Honshu facing the Japan Sea.

Although shallow historical large earthquakes and microseismicity show a clear lineaments along the coastline (Gutscher 2001; Kawanishi et al. 2009), no major active faults have been identified in the San-in region (HERP 2017). A detailed geomorphological study suggests that ENE–WSW trending dextral active faults and NNW–SSE trending sinistral ones are distributed in the San-in region, but that they are young developing faults with cumulative offsets of less than a few hundreds of meters (Okada 2002).

Owing to a nationwide GNSS network installed in mid 1990s, contemporary deformation of the Japanese Islands is monitored in detail. Sagiya et al. (2000) analyzed the GNSS data and found a concentrated region of strain rates far from major plate boundaries including the Nankai Trough and Japan Trench in central Japan. However, they did not identify concentration of strain rates in the San-in region. Loveless and Meade (2010) studied the GEONET data to clarify velocity profile across the NCSZ

*Correspondence: nishimura.takuya.4s@kyoto-u.ac.jp
[1] Disaster Prevention Research Institute, Kyoto University, Uji 611-0011, Japan
Full list of author information is available at the end of the article

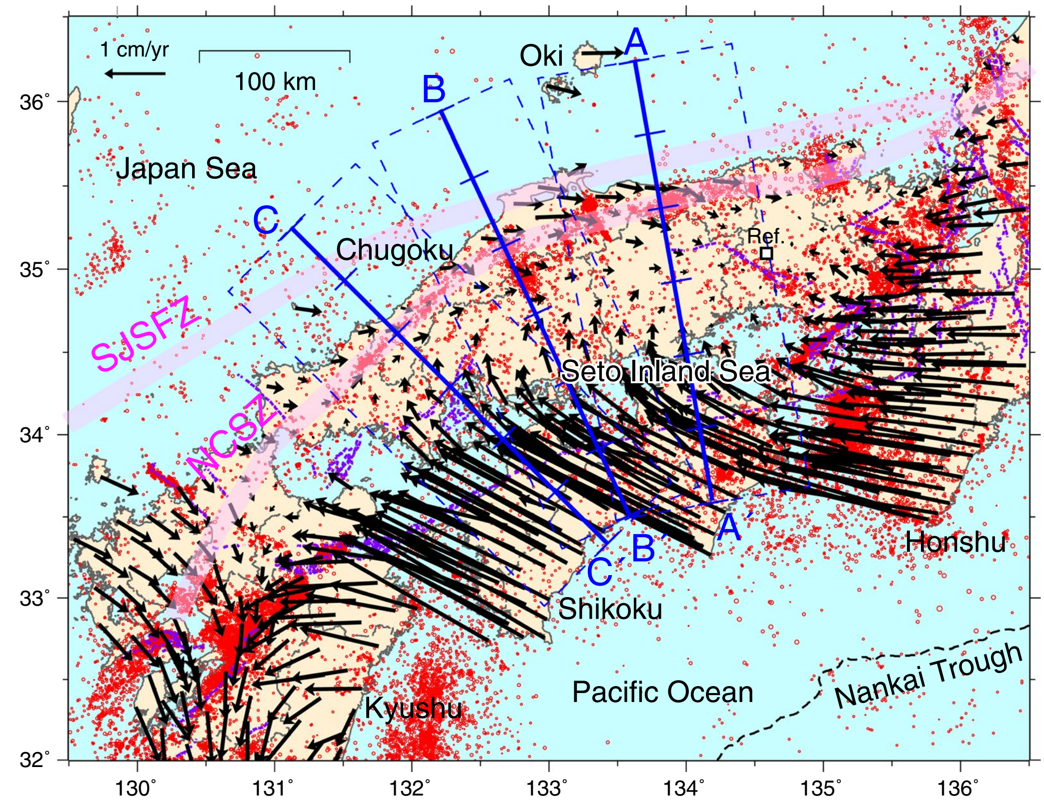

Fig. 1 GNSS velocities in southwest Japan from April 2005 to December 2009. A reference station of the velocities is 950344 (Hyogo-Ichinomiya). The Northern Chugoku Shear Zone (NCSZ) and Southern Japan Sea Strike Slip Fault Zone (SJSFZ) are right-lateral shear zones proposed by Gutscher and Lallemand (1999) and Itoh et al. (2002), respectively. *Purple broken lines* are major active faults (HERP 2017). *Red dots* show a shallow seismicity with magnitude of ≥2 and a depth of <30 km during 1923–2016. *Three broken rectangles* show locations of velocity profile (Fig. 2). *Ticks on lines* in the *rectangles* are plotted with an interval of 50 km

and construct the block model of the Japan region. They showed ≤3 mm/year of right-lateral slip rates along the NCSZ in the block model but no significant relative motion in the velocity profile across the NCSZ. They, therefore, concluded that the NCSZ does not play an important role in the larger-scale tectonics of Western Honshu. No other geodetic studies have pointed out right-lateral movements in the San-in region.

Several large earthquakes including the 2000 M_{JMA} (magnitude determined by the Japan Meteorological Agency) 7.3 western Tottori earthquake and the 2016 M_{JMA}6.6 central Tottori earthquake occurred in the San-in region, which means that the region is seismotectonically active. However, GNSS data in the region have not been fully examined although the number of GNSS stations has been increased by ~50% in the twenty-first century. In this paper, we examine a dense GNSS data to clarify whether significant movements are ongoing in the San-in regions and model the movements with a simple dislocation model. We also discuss a distribution of microseismicity in a shear zone.

GNSS velocity data

We use data of continuous GNSS stations of the GNSS Earth Observation Network System (GEONET) (cf. Sagiya et al. 2000). We estimate secular GNSS velocities in a period from April 2005 to December 2009. There were no earthquakes and slow slip events causing significant crustal deformation in southwest Japan during this period. The velocities are estimated by fitting linear, annual, and semiannual terms to daily coordinates of the GEONET F3 solution (Nakagawa et al. 2009). Uncertainties of the horizontal velocities assuming a white noise model are 0.02–0.05 mm/year. Although these values can be underestimated by an order because the noise characteristics of GNSS time series are time-correlated (e.g., Mao et al. 1999), velocity errors are so small that we can ignore the data errors in the following analysis. Figure 1 shows horizontal velocities with respect to the 950344 station. We remove several vectors at anomalous stations which are inconsistent with velocities at surrounding stations. We found monuments of the anomalous stations are mostly inclined by visual inspection. Although the most distinctive feature of Fig. 1 is velocities toward WNW along the Pacific coast, which is caused by interplate coupling between the subducting Philippine Sea and the overriding Amurian plates (e.g., Yoshioka and Matsuoka 2013), eastward velocities along the coastline of the Japan Sea between ~132.5°E and ~135°E are recognized with respect to the reference station. These eastward velocities are small in the southern side of the NCSZ corresponding to a zone of active shallow microseismicity. Deformation rates across the NCSZ are clarified by projections of velocity profiles. Figure 2a–c shows velocity profiles along sections *A*–*A*′, *B*–*B*′, and *C*–*C*′ across the NCSZ shown in Fig. 1, respectively. Velocity components shown in Fig. 2a–c are N80°E, N65°E, and N45°E components perpendicular to the sections, respectively. Along section *A*–*A*′ (Fig. 2a), distinctive velocity gradient in a distance of ≤−100 km is mainly attributed to elastic deformation due to interplate coupling along the Nankai Trough. Velocities between −100 and −30 km are almost constant, which means lower deformation rates between the Seto Inland Sea and Chugoku Mountains. We identify steep velocity gradient around a distance of 0 km. The velocities there shift from ~1 to ~4 mm/year with a transition width of ~50 km. No significant difference of velocities between the coastline of Japan Sea (distance ~30 km) and Oki Island (distance ~90 km). On the other hand, no significant gradients in velocities are recognized in a distance between −100 and 100 km along section *C*–*C*′. Along section *B*–*B*′, gradient is recognized around a distance of 0 km and gentler than that along *A*–*A*′. Because there are no clear gradients of velocity components parallel to the sections around a distance of 0 km either, the contemporary deformation is concentrated only in an eastern part of the NCSZ. The

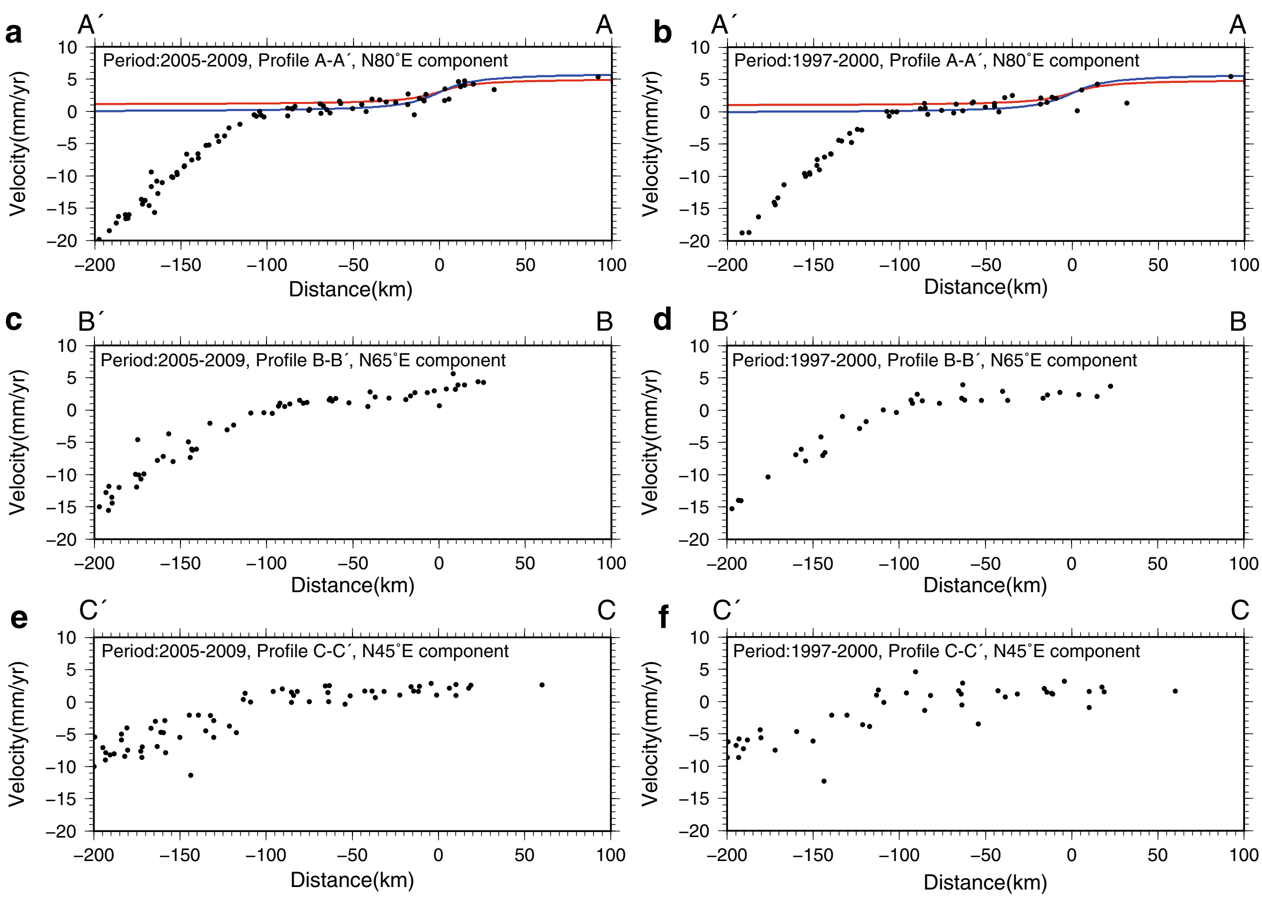

Fig. 2 Velocity profile across the NCSZ. Plotted velocities show a component perpendicular to the profiles. **a** Velocities along profile *A*–*A*′ from April 2005 to December 2009. *Red and blue curves* are calculated velocities of elastic dislocation models for a vertical strike slip fault with a creeping rate of 4 and 6 mm/year, respectively. **b** Same as **a** but from July 1997 to June 2000. But profile *B*–*B*′. **c** Velocities along profile *B*–*B*′ from April 2005 to December 2009. **d** Same as **c** but from July 1997 to June 2000. **e** Velocities along profile *C*–*C*′ from April 2005 to December 2009. **f** Same as **c** but from July 1997 to June 2000

analysis of strain rates (Nishimura et al., submitted manuscript) also suggests that high strain rates are concentrated along the NCSZ between 132.7°E and 135.2°E. We propose to call this concentrated deformation zone as the San-in shear zone (SSZ).

Deformation modeling and discussion

High velocity gradients can be explained by a simple elastic dislocation model. We assume a two-dimensional vertical fault with right-lateral strike slip. The fault is locked from surface to a locking depth and creeps below the locking depth to infinity. The surface velocity parallel to the fault with an elastic half-space is a symmetric pattern of arctangent with respect to the fault (Savage and Burford 1973). The calculated velocities are shown by red and blue curves with a creeping rate of 4 and 6 mm/year and a locking depth of 16 km (Fig. 2a). The calculated velocities roughly reproduce the observed ones around a distance of 0 km. Least square fitting for the data at a distance between −100 and 100 km suggests 6.4 ± 1.0 mm/year and 28 ± 10 km for a creeping rate and a locking depth, respectively, but the estimated creeping rate may be an upper bound due to ignoring other deformation sources including interplate coupling along the Nankai Trough. The estimated locking depth is significantly deeper than a cutoff depth of crustal seismicity (~10 km) (Omuralieva et al. 2012), but it must be affected by ignoring variations of the locking depth and fault geometry along the SSZ. Although it is difficult to resolve these problems from the limited sparse GNSS data, a comparison between the observed and calculated velocities suggests the right-lateral strike movements beneath a locking depth at a rate of ~5 mm/year along the SSZ.

Another possibility to cause strain rate concentration in the SSZ is postseismic deformation of recent large earthquakes including the 1927 M_{JMA}7.3 Tango, the 1943 M_{JMA}7.2 Tottori, and the 2000 M_{JMA}7.3 western Tottori earthquake. Viscoelastic relaxation of a large earthquake generally continues for more than several decades. We use a layered viscoelastic half-space model (Wang et al. 2006) to calculate postseismic deformation due to viscoelastic relaxation with varying Maxwell viscosities of upper mantle and lower crust. If viscosities of upper mantle and lower crust are, respectively, assumed to be 5×10^{18} and 5×10^{19} Pa s which are estimated from postseismic deformation of the 1927 Tango earthquake (Tabei 1989), surface velocity in 2005 is less than 1.3 mm/year. If we assume viscoelastic lower crust is an order of 10^{19} Pa s, the strain rate concentration near the SSZ can be reproduced qualitatively. However, the viscoelastic model cannot reproduce observed eastward velocity in an area a 1000 km north of the SSZ because a scale of deformation due to calculated viscoelastic relaxation is less than a few 100 km. The observed velocity in the remote area including Korean Peninsula and the China continent is eastward and similar to that on Oki Island (Nishimura et al. submitted manuscript), which can be regarded as a rigid block motion north of the SSA. We, therefore, conclude that postseismic deformation is not a main cause of ongoing deformation in the SSZ.

The apparent concentration of strain rates along the SSZ makes us to question why previous GNSS studies did not notice the SSZ. Loveless and Meade (2010) examined velocities around the NCSZ and found no significant deformation. We suggest two possibilities for apparent difference. First, concentration of strain rates is observed only in the SSZ, not all over the NCSZ. Second, distribution of GNSS stations before 2002 is not enough to detect concentration of strain rates in the SSZ. We plot velocity profiles along sections *A*–*A*′, *B*–*B*′, and *C*–*C*′ during July 1997–June 2000 (Fig. 2b, d, f). A velocity gradient is unclear at a distance of 0 km along sections *A*–*A*′ because few stations locate north of the SSZ (Fig. 2b). After 2002, several new stations have been installed and some stations showing local deformation have been replaced around the SSZ. Therefore, it is clear in the velocity profile after 2005 (Fig. 2a). Because of no velocity change on Oki Island (around a distance of 90 km in Fig. 2a, b), the apparent temporal change of the velocity profile is probably caused by artificial redistribution of the GNSS network.

The SSZ is generally oriented in an azimuth of N70–80°E along the coastline, and the observed velocities are well explained by right-lateral strike slip movements of the SSZ as explained in the previous section. However, each cluster of microseismicity within the SSZ is oriented in NNW–SSE (Fig. 3) and finite fault models for recent large earthquakes (cf. Nishida 1990; Sagiya et al. 2002) also suggest left-lateral strike slip on faults whose strike is NNW–SSE, except for the 1943 Tottori earthquake (Kanamori 1972) whose strike is N80°E with right-lateral strike slip. We propose that the NNW–SSE faulting is conjugate Riedel shears in a shear zone (Fig. 3). Numerous cracks and structures in addition to principal displacement shears develop in a shear zone with a scale from a shear experiment in laboratory to surface rupture in field (cf. Tchalenko 1970). The formation of Riedel shears and conjugate Riedel shears is explained by fracture planes under maximum compressional stress in the shear zone with the Mohr–Coulomb failure criterion. The maximum compressional stress estimated from focal mechanisms of earthquakes in the San-in shear zone (Kawanishi et al. 2009) lies with an angle of ~45° with respect to the orientation of the shear zone (Fig. 3). Conjugate Riedel shears develop at an early stage of the shear zone formation according to the laboratory experiments (Tchalenko

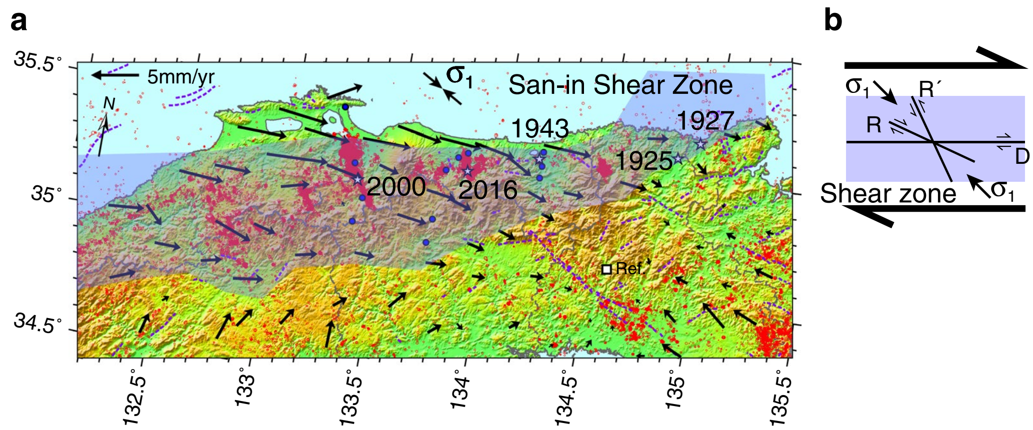

Fig. 3 **a** GNSS velocities, shallow seismicity, and active faults in and around the San-in shear zone (SSZ). *Purple broken lines* are active faults (Research Group for Active Faults in Japan 1991). *Red dots* are seismicity with magnitude of ≥1 and a depth of <30 km during 1998–2016. *White stars* are epicenters of shallow $M \geq 6.5$ earthquakes with their occurrence year. *Blue circles* are new GNSS stations installed in 2014. A direction of maximum compressional stress in the SSZ (Kawanishi et al. 2009) is indicated by a couple of *arrows*. **b** Schematic Riedel shear in a shear zone. *D*, *R*, and *R*′ are principal displacement shear, Riedel shear and conjugate Riedel shear, respectively

1970). There are no single active faults regarded as a principal displacement shear but young active faults with a strike of ENE–WSW or NNW–SSE in the SSZ (Okada 2002). These manifest that the SSZ is a young and developing shear zone in a geological time scale.

The SSZ locates along a volcanic front of the subducting Philippine Sea plate. Low velocity of seismic waves in upper mantle beneath the SSZ and a high $^3He/^4He$ ratio suggest upwelling fluid from the mantle in the SSZ (Nakajima and Hasegawa, 2007; Sano and Nakajima 2008). These observations suggest that the fluid weaken the lower crust (i.e., Iio et al. 2002). High temperature induced from high heat flow (Tanaka et al. 2004) and the shallow cutoff depth of seismicity (Omuralieva et al. 2012) also contribute to weaken the lower crust in the SSZ. Oblique subduction of the Philippine Sea can drive the aseismic faulting or ductile flow in the weakened lower crust examined by Kawanishi et al. (2009) and this study. We propose that the SSZ is a shear zone for strain partitioning within the continental plate and accommodates a part of relative motion between the subducting Philippine Sea and the overriding continental plates, as suggested by previous studies (Tsukuda 1992; Gutscher and Lallemand 1999; Gutscher 2001). Although the concentration zone of strain rates observed by GNSS is limited between 132.7°E and 135.2°E, similar movements probably extend to east and west. Because we do not identify the concentrated deformation in eastern and western extensions on land, we speculate that right-lateral strike slip movements are more diffusive in the extensions and are accommodated mainly in an offshore region.

We constructed 13 continuous GNSS stations across the SSZ to clarify a detailed deformation in and around the SSZ in 2014 as denoted by blue circles in Fig. 3. These stations observed near field co- and postseismic displacement of the M_{JMA} 6.6 central Tottori earthquake occurred in October 21, 2016. A further analysis including these data on the SSZ will be presented in near future.

Conclusions

We analyzed GNSS data in southwest Japan and found a concentrated deformation zone along the coastline of the Japan Sea between 132.5°E and 135°E. This zone is a part of the Northern Chugoku Shear Zone based on a seismological and geological study (Gutscher and Lallemand 1999). This study has first identified the concentrated shear zone in the San-in area geodetically, and we propose to call the concentrated deformation zone the San-in shear zone (SSZ), which accommodates a right-lateral strike slip movement with a width of ~50 km. A simple dislocation model of vertical dextral fault with a shallow locking and a deep creeping of ~5 mm/year reproduces the observed velocity pattern across the SSZ. Although the SSZ is characterized by active shallow microseismicity, each cluster of microseismicity and faults ruptured by recent large earthquakes are almost oriented in NNW–SSE which is oblique to the overall trend of the SSZ. We propose the oblique seismicity is attributed to conjugate Riedel shears in a young developing shear zone. From the view point of regional tectonics, it is proposed that the SSZ is a shear zone for strain partitioning within the southern margin of the continental Amurian plate and accommodates a part of relative motion of the subducting Philippine Sea plate.

Abbreviations

GEONET: GNSS Earth Observation Network System; GNSS: Global navigation satellite system; M_w: Moment magnitude; M_{JMA}: Magnitude of the Japan Meteorological Agency scale; NCSZ: Northern Chugoku fault zone; SJSFZ: Southern Japan Sea fault zone; SSZ: San-in shear zone.

Authors' contributions

TN designed and conducted all of this study and wrote the manuscript. YT helped installing stations and interpreting the data and revised the manuscript. Both authors read and approved the final manuscript.

Author details

[1] Disaster Prevention Research Institute, Kyoto University, Uji 611-0011, Japan. [2] Graduate School of Science, Hokkaido University, Sapporo 060-0810, Japan.

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Competing interests

Both authors declare that they have no competing interests.

Availability of data and materials

GNSS velocity data used in this study are available by requesting the corresponding author by e-mail.

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